

# Carbon cycle dynamics - How are major carbon sinks and sources varying with global change?

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The entire Earth System, atmosphere, oceans, biology and geology are involved in the carbon cycle (Archer 2010). Carbon dioxide is taken up by the land biosphere through photosynthesis, and released through respiration and combustion (Schimel et al. 2001). The oceans take up carbon through closely coupled physical, chemical and biological processes (Sarmiento and Gruber 2006). They absorb carbon dioxide in regions where mixing and biological activity maintain low ocean carbon dioxide levels, allowing chemical diffusion from these active regions of the sea. In other regions, carbon-rich water mixes to the surface and releases carbon to the atmosphere. These processes are natural and have always occurred.

The anthroposphere, the sphere of human activities, transforms this cycle in two ways. First, humans burn carbon from geological reservoirs that would normally be stable over millions of years and introduce this additional carbon into the more active atmosphere-ocean-land system, increasing the total amount of carbon circulating in the Earth System (Archer 2010). Second, human land use converts biologically stored carbon in soils and plants to carbon dioxide in the atmosphere, changing the balance of stored and circulating carbon (Schimel 1995).

These human activities increase atmospheric carbon dioxide and thereby

the trapping of heat in the atmosphere, leading to global climate change. As climate changes, it has consequences for the carbon cycle. The rates of many biogeochemical processes, such as photosynthesis, respiration, nitrogen cycling and wildfire increase in warmer conditions (Field et al. 2007). These higher process rates may speed up biological activity, producing potential positive and negative feedbacks to the carbon cycle. In some models, the feedback effects of the carbon cycle influence atmospheric  $\text{CO}_2$  by tens to even hundreds of parts per million, corresponding to significant effects on temperature (Cox et al. 2000). Temperature effects may be largest in high latitude regions, where enormous post-glacial deposits of carbon in permafrost could be released as  $\text{CO}_2$  and methane as these soils thaw (Koven et al. 2011).

Precipitation also changes as the warming atmosphere causes more evaporation. This intensification of the hydrological cycle will cause some regions to become wetter, but arid regions may become drier. Drier conditions in the tropics will decrease plant growth and reduce carbon storage in these regions (Fung et al. 2005). Warmer and wetter conditions in mid-latitude regions may actually increase carbon storage. Most evidence suggests the tropical effects are larger, leading to overall release of ecosystem carbon stores. This creates a global feedback

increasing atmospheric carbon dioxide as temperatures warm.

When humans burn fossil fuels, they transform organic carbon compounds that last for millions of years into atmospheric carbon dioxide. The uptake and stabilization of carbon dioxide into long-lived carbon compounds – which defines the lifetime of carbon dioxide – takes a lot of time. While photosynthesis and air-sea gas exchange can draw  $\text{CO}_2$  concentrations down quickly, i.e. within years, actually transferring that carbon into stable chemical forms, safe from recycling back to the atmosphere requires ten to thirty thousand years (Archer 2010).

Because of the long lifetime of changes to the carbon cycle, the paleo-perspective is critical. For example, paleorecords tell us that while atmospheric carbon dioxide concentrations can increase quite rapidly, it can take much, much longer for it to be locked into long-lasting forms and provides a timescale for these dynamics. During one well-documented event 55 million years ago, atmospheric carbon dioxide nearly doubled over about 20,000 years, with an accompanying increase in temperature of perhaps  $6^\circ\text{C}$ . While atmospheric carbon dioxide increased very rapidly, it took nearly 7-8 times longer to return to previous levels (Doney and Schimel 2007).

Carbon scientists are finding creative ways to combine paleodata, process studies and modern-day observations to model the “fast out-slow in” processes that determine the longevity and severity of climate change. The paleorecord provides an essential observational basis for assessing the reality of model-based scenarios of the long-term future.

## Selected references

Full reference list online under:

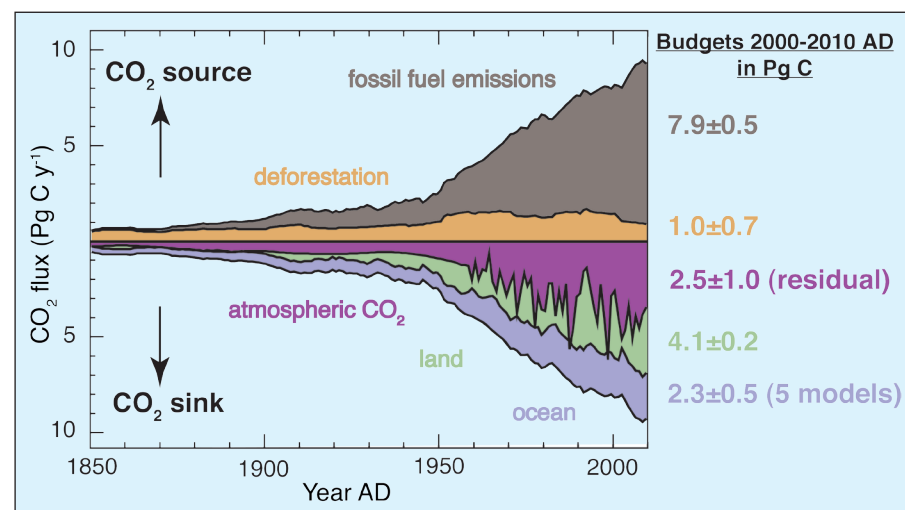
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Figure 1: Human perturbation of the global carbon budget over the period 1850–2012 AD. The values on the right represent the amount of C emitted and absorbed during the last decade (2000–2010 AD). Figure modified from Global Carbon Project (2011), updated from Le Quééré et al. (2009) and Canadell et al. (2007).

Paleoclimate data are essential to gauge the magnitude and the speed of change in greenhouse gas concentrations, ocean acidification, and climate. These parameters co-determine the anthropogenic impacts on natural and socioeconomic systems and their capabilities to adapt.

Concentrations of the three major anthropogenic greenhouse gases were much smaller during at least the last 800 ka than modern and projected concentrations. The ice core record reveals that the average rate of increase in  $\text{CO}_2$  and the radiative forcing from the combination of  $\text{CO}_2$ ,  $\text{CH}_4$ , and  $\text{N}_2\text{O}$  occurred by more than an order of magnitude faster during the Industrial Era than during any comparable period of at least the past 16 ka (Joos and Spahni 2008). This implies that current global climate change and ocean acidification is progressing at a speed that is unprecedented at least since the agricultural period.

Ice, terrestrial and oceanic records reveal huge changes in climate during glacial periods on the decadal time scale (Jansen et al. 2007). These are linked to major reorganizations of the oceanic and atmospheric circulations, including a stop and go of the poleward

Atlantic heat transport and shifts in the rain belt of the Inter Tropical Convergence Zone (ITCZ). These “Dansgaard-Oeschger” and related Southern Hemisphere climate swings demonstrate that the climate system can switch into new states within decades – a potential for unpleasant future surprise.

Surprisingly, variations in atmospheric  $\text{CO}_2$  remained quite small during Dansgaard-Oeschger events. This indicates a certain insensitivity of atmospheric  $\text{CO}_2$  to shifts in the ITCZ, changes in the ocean’s overturning circulation, and abrupt warming of the boreal zone. Related variations in  $\text{N}_2\text{O}$  and  $\text{CH}_4$  are substantial (Schilt et al. 2010), but the resulting radiative forcing is several times smaller than current anthropogenic forcing. Greenhouse gas concentrations react to climate change and amplify it, but the data may also indicate that such an amplification of man-made climate change may remain moderate compared to anthropogenic emissions. This is in line with results from Earth System Models and probabilistic analyses of the last millennium temperature and  $\text{CO}_2$  records (Frank et al. 2010).

Theories and Earth system models must undergo the reality check to quantitatively

explain the observations. For example, reconstructed and simulated spatio-temporal evolution of C-cycle parameters during the last 11 ka (Fig. 1) provide evidence that the millennial-scale  $\text{CO}_2$  variations during the Holocene are primarily governed by natural processes (Menviel and Joos 2012), in contrast to previous claims of anthropogenic causes.

Paleoscience allows us to test hypothesis. Can we mitigate the man-made  $\text{CO}_2$  increase by stimulating marine productivity and promoting an ocean carbon sink by artificial iron fertilization? Paleodata (Röthlisberger et al. 2004) and modeling suggest that we can’t – past variations in aeolian iron input are not coupled to large atmospheric  $\text{CO}_2$  changes.

Warming might set carbon free from permafrost and peat or  $\text{CH}_4$  currently caged in clathrates in sediments, which would in turn amplify global warming and ocean acidification. However, soil, atmospheric  $\text{CO}_2$  and carbon isotope data suggest a carbon sink, and not a source, in peatlands during periods of past warming (Yu 2010). Likewise, ice core data show no extraordinarily large  $\text{CH}_4$  variations nor supporting isotopic signatures (Bock et al. 2010) for thermodynamic conditions potentially favoring  $\text{CH}_4$  release from clathrates, i.e. during periods of rapid warming and sea level rise.

Yet, it is not always clear to which extent a comparison of the past with man-made climate change is viable. We need to improve our mechanistic understanding of the underlying processes to better assess the risk of ongoing greenhouse gas release and associated climate amplification and feedbacks in order to better guide emission mitigation and climate adaptation efforts. Paleoresearch, offering unique access to time scales and complex climate variations neither covered in the instrumental records nor accessible by laboratory studies, is the key to reach this policy-relevant goal, but its potential has barely been exploited.

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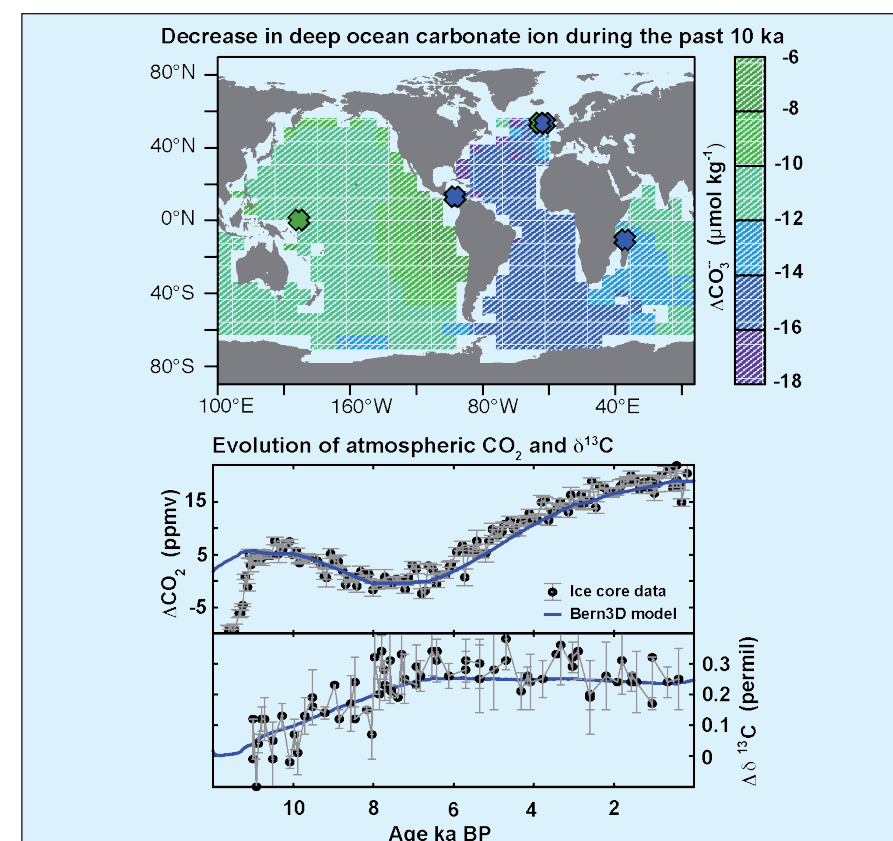
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Figure 1: Evolution of atmospheric  $\text{CO}_2$  and  $\delta^{13}\text{C}$  of atmospheric  $\text{CO}_2$  (lower panel) and changes in deep ocean carbonate ion concentration ( $\mu\text{mol kg}^{-1}$ ) over the last 10 ka (upper panel). Proxy data are shown by circles and crosses, and results from the Bern3D model by blue lines and color contours (after Menviel and Joos 2012).